Some Combustion Studies of Alberta Coals

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Foreword

Since 1976, numerous projects have been initiated in Alberta by industry and by academic research institutions which are aimed at better utilization of Alberta's energy resources.

These research, development and demonstration efforts were funded by the Alberta/Canada Energy Resources Research Fund (A/CERRF), which was established as a result of the 1974 agreement on oil prices between the federal government and the producing provinces.

Responsibility for applying and administering the fund rests with the A/CERRF Committee, made up of senior Alberta and federal government officials.

A/CERRF program priorities have focused on coal and conventional energy resources, as well as energy conservation and renewable energy. Program administration is provided by staff within the Scientific and Engineering Services and Research Division of Alberta Energy.

In recognition of the importance of coal to Alberta's economy, the Alberta Office of Coal Research and Technology was established in 1984 within Alberta Energy and Natural Resources (now Alberta Energy). Its primary purpose is to encourage the development and application of new technologies related to Alberta coals. The Office provides funding contributions to research and development projects in industry, academic institutions and other research establishments and monitors their progress in an overall program of improving the production, transportation and marketability of Alberta coals.

In order to make research results available to industry and others who can use the information, highlights of studies are reported in a series of technology transfer booklets. For more information about other publications in the series, please refer to page 13.

Some Combustion Studies of Alberta Coals

Recent advances in the science of coal combustion have resulted in combustion technologies that achieve optimum performance from coals having narrowly specified properties. Consequently, coal producers who wish to sell coal to the users of these technologies must be prepared to provide detailed information about the combustion characteristics of their coals.

This requires more than the conventional testing involved in ultimate and proximate analyses. It means new or improved laboratory-scale combustion testing methods must be developed that not only simulate coal burning in thermal plants, but, ideally, can minimize the need for expensive, full-scale combustion tests used in the past. Nonetheless, a full-fledged coal combustion research program should combine small-scale empirical studies, fundamental investigations, pilot-scale work and full-scale burn tests if reliable predictions are to be made about a particular coal's combustion performance.

With this as a background, the Alberta/Canada Energy Resources Research Fund (A/CERRF) supported several coal combustion research projects beginning in 1985. These projects were administered by the Alberta Office of Coal Research and Technology.

Initial Combustion Studies

During a major investigation at the Alberta Research Council (ARC) of processes that might be used to liquefy Alberta coals, hydropyrolysis of pulverized subbituminous coal in the presence of hydrogen gas at high temperatures and pressures was studied. In addition to producing liquids, the process also resulted in a carbon-enriched char. When the combustion characteristics of this char were measured, it appeared that the char could totally or partly supply the fuel requirements of a coal-fired thermal boiler. The combustion measurements were made with a thermogravimetric analyser, and two entrained flow combustors (a drop tube combustor and a laminar flow combustor) constructed at ARC for this research program.

It was observed that when the entrained flow combustors were used, chars resulting from severe hydropyrolysis conditions burned faster and more completely than chars resulting from less severe processing conditions. In fact, char produced at 800°C burned faster than the parent coal. These results were opposite to those from thermogravimetric analysis. They suggested to Alberta Research Council researchers that diffusion of oxygen into the porous char structure was controlling the combustion rate on the entrained flow combustors. Therefore, to obtain a better understanding of the combustion mechanism, seven chars having different physical properties were produced and combusted. An attempt was made to relate surface characteristics to combustion behaviour.

Char surface characteristics were measured by helium density, mercury porosimetry, and nitrogen and carbon dioxide adsorption methods. Special procedures were developed for the adsorption methods to allow surface area measurements on samples smaller than one gram. The helium density and mercury porosimetry data were used to calculate the total open-pore volume of the chars.

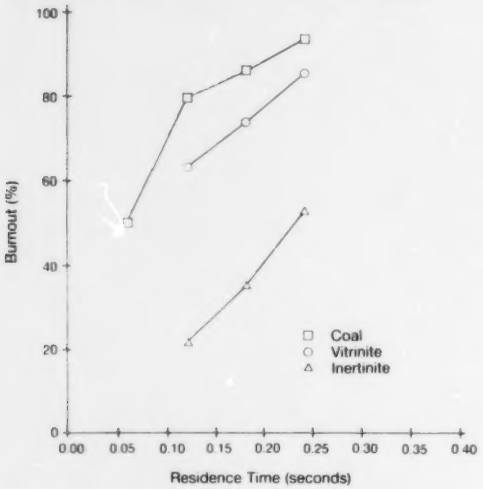
A mathematical model of particle reaction rate and mass transfer was developed to allow interpretation of thermogravimetric analysis and entrained flow combustion data. Also, a pore diffusion model was developed to account for the effect of diffusion limitations within the particle during char particle combustion. As a result, good agreement was achieved between the model's predictions and the actual combustion data.

This work emphasized the importance of the pore structure of a solid fuel and its effect on combustion properties. The chemical reactivity (as measured by thermogravimetric analysis), as well as pore diffusion and gas phase reactions occurring near the burning particle, must be considered when interpreting data from coal or char combustion experiments.

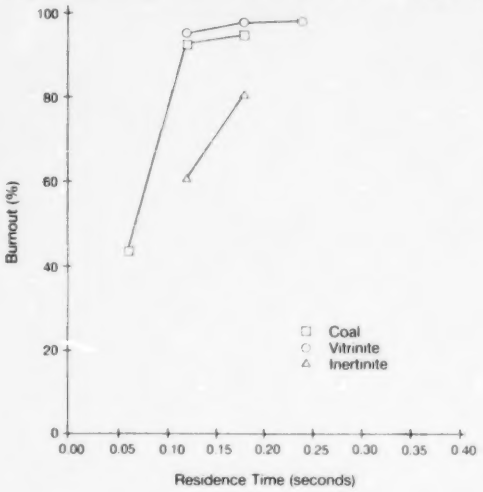
While these investigations were under way, ARC researchers were also aware that previous coal combustion studies had revealed an apparent relationship between combustion properties and the presence of certain discrete, organic, microscopically identifiable particles known as macerals. Consequently, measurements were made of the combustion reactivity of chars prepared from (1) inertinite and vitrinite macerals which had been hand-picked from four Alberta coals, and (2) the parent coals. Combustion rates were measured on a thermogravimetric analyser and an entrained flow combustor at ARC, and on a single particle combustor at Sandia National Laboratories in California. The structure of partially combusted chars was examined with a scanning electron microscope.

Burnout Profile of Parent Coal and Macerals in an Entrained Flow Combustor (furnace temperature 1100°C)

High-Volatile Bituminous C Coal – 9% O_2



High-Volatile Bituminous C Coal – 21% O_2 (air)



(Source: *Combustion Properties of Macerals from Four Alberta Coals*, Chambers A., K. Knill and D. Unganan, Alberta Research Council, March 1987)

Maceral Content of Coals and Maceral Concentrates

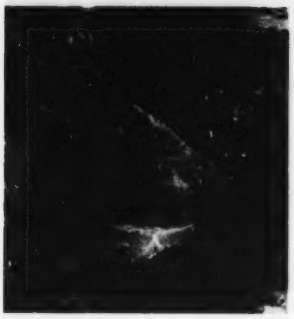
Coal	Rank	Fraction	Vitrinite	Exinite (volume % daf)	Inertinite
A	low-volatile bituminous	whole coal	82	0	18
		vitrinite	97	0	3
		inertinite	43	0	57
B	high-volatile bituminous C	whole coal	86	0	14
		vitrinite	95	2	3
		inertinite	25	1	74
C	high-volatile bituminous C	whole coal	94	0	6
		vitrinite	97	0	2
		inertinite	41	0	59
D	subbituminous B	whole coal	78	2	20
		vitrinite	97	0	3
		inertinite	33	0	67

(Source: *Combustion Properties of Macerals from Four Alberta Coals*, Chambers, A., K. Knill and D. Ungarian, Alberta Research Council, March 1987)

The most significant observations from this work were as follows:

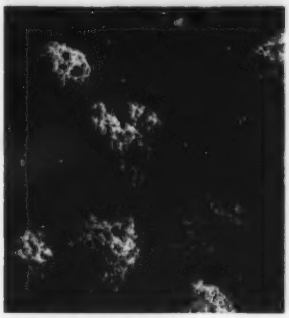
- differences between coal rank were much larger than differences between macerals within a given rank. Alberta subbituminous and high-volatile coals were very reactive, with greater than 90 per cent burn-off after only 0.15 second. A low-volatile coal had only 40 per cent burn-off after 0.35 second under the same conditions;
- for the three reactive coals, the vitrinite maceral and the parent coal had up to twice the initial weight loss as the inertinite maceral during devolatilization and volatiles combustion. For each coal, however, combustion reactivity of the remaining chars was similar for the different maceral components;

Physical Structure of Partially Combusted Coals



Original coal particles.

Partially Combusted Char from Low-Reactivity Coal.



Partially Combusted Char from High-Reactivity Coal.

(Scanning Electron Micrographs courtesy of Alberta Research Council)

- scanning electron microscopy revealed that changes occurred in the particle structure of some samples. These changes appeared to correlate with different rates of combustion; and
- the inertinite content appears to be directly related to the amount of unburnt carbon that will appear in flyash. This is caused primarily by the differences in the initial loss of volatile matter.

Influence of Porosity on Combustion

To develop further the hypothesis that porosity can play a major role in coal combustion, and to provide more information for a mathematical model describing the relationship between char porosity and combustion behaviour, an investigation was undertaken at ARC involving a range of coal types. Specifically, subbituminous, high-volatile bituminous and low-volatile bituminous coals were burned in a laminar flow combustor which fires 3 kg/h of pulverized sample in a self-sustaining flame.

As observed in earlier work, the subbituminous and high-volatile bituminous coals were very reactive, with burnout of 95 and 88 per cent, respectively. They produced a stable flame and burned near the inlet of the combustor. The low-volatile bituminous coal, however, was not as reactive (achieving a maximum burnout of 72 per cent) and burned near the outlet of the combustor. As a result, a stable flame could not be sustained.

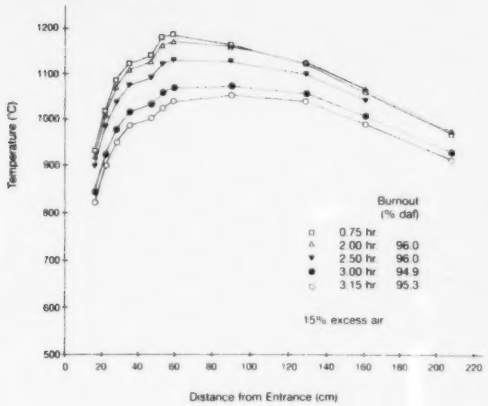
Partially burnt chars were collected and analyzed to determine changes in particle size, density porosity and surface area during combustion. The subbituminous and high-volatile bituminous coals burned with decreasing particle size, while the low-volatile bituminous coal burned at approximately constant size after some slight swelling. Despite the limitations of the mercury porosimetry method, differences in pore volume for the reactive and non-reactive coals were observed. The low-volatile bituminous coal had a large initial pore volume which did not change appreciably during combustion. Both the subbituminous and high-volatile bituminous coals underwent large increases in pore volume as burnout increased. Surface area measurements made on the subbituminous coal showed that most of the area was originally contained in micropores which opened during combustion. The surface area of the chars from all three coals passed through a maximum at about 75 per cent burnout.

To understand the relationships between porosity and other factors which may influence char burnout, a single particle combustion model was developed. It concentrated on the heat, as well as mass transfer and chemical reactions occurring in the gases immediately surrounding a burning particle. This model allows particle temperatures and conversions to be predicted for various particle sizes, gas temperatures and gas compositions under conditions typical of pulverized coal combustors and gasifiers.

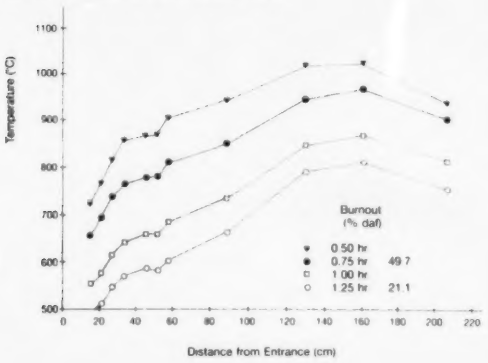
With these experimental data as a background, combustion testing procedures were used to evaluate the combustion performance of some upgraded coals and some blends of coals.

Laminar Flow Combustion
Wall Temperature Profile

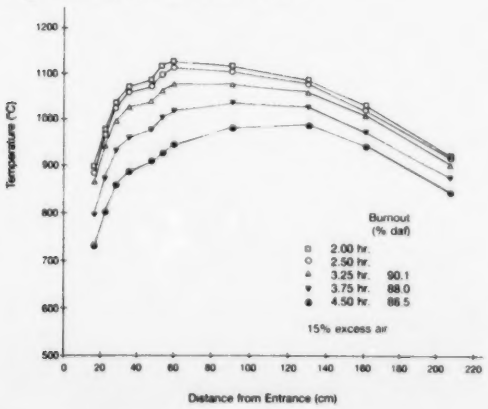
Subbituminous Coal



Low-volatile Bituminous Coal



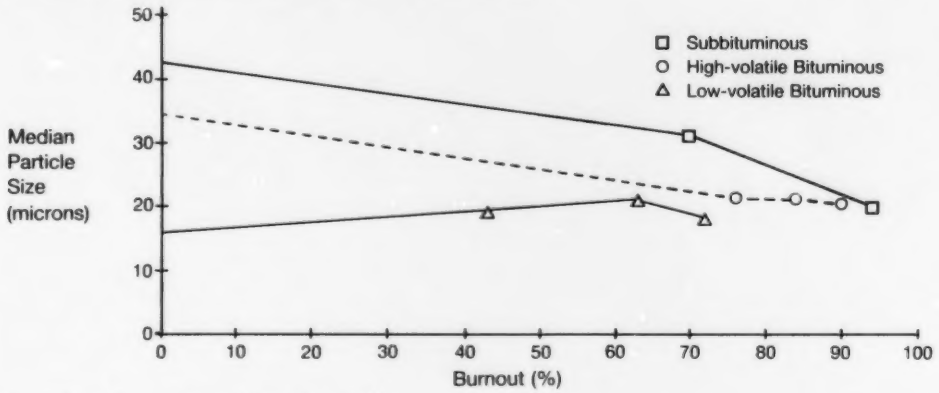
High-volatile Bituminous Coal



(Source: *Physical Structure Changes of Alberta Coals During Combustion*, Malychuk, A., A.K. Chambers, R. Zacharkiw and D.E. Ungarian, Alberta Research Council, July 1988)

Entrained Flow Combustor (top) and Thermogravimetric Analyser (bottom) used in coal combustion studies at the Alberta Research Council

Median Particle Size of Partially Burnt Coal Samples



(Source: *Physical Structure Changes of Alberta Coals During Combustion*, Malychuk, A., A.K. Chambers, R. Zacharkiw and D.E. Ungarian, Alberta Research Council, July 1988)

Combustibility of Upgraded Alberta Coals

Several research projects supported by the Alberta Office of Coal Research and Technology have demonstrated that Alberta coals can be upgraded by a variety of processes. These range from relatively simple techniques that remove some moisture, to more complex procedures, such as agglomeration, which lower both the moisture and mineral contents of coal and supplement the energy content.

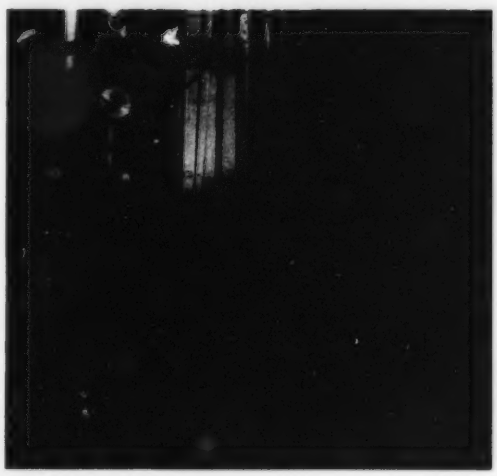
While proximate analysis and determination of heating value indicate that these upgraded coals are improved relative to their parent coals, little is known about their combustion behaviour.

Consequently, a high-volatile, low-rank coal, upgraded by a process developed by Gulf Canada, was tested on the three combustion test units available at the Alberta Research Council to determine its combustion performance relative to the parent coal.

Six upgraded coal samples, prepared at different treatment temperatures, and the parent coal were tested using thermogravimetric analysis and entrained flow combustion. The thermogravimetric tests indicated that all the treated samples had higher ignition, maximum rate and combustion completion temperatures. This implied that the treated coals may have poorer ignition properties than the raw coal, but burnout properties were comparable to the raw coal. Combustion testing also showed that coal samples treated at temperatures below 250°C had poorer combustion properties than either the raw coal or samples treated at temperatures above 250°C.

Further combustion tests were performed at a larger scale on a laminar flow combustor. Two samples, produced under promising upgrading conditions, and the parent coal were tested. Both of the treated samples gave combustor temperature profiles and per cent carbon burnouts similar to, or better than, the parent coal.

Temperature profiles from the combustor showed that the coal and treated samples were very reactive, with most of the combustion occurring in the first half of the combustor. These results illustrate the importance of performing combustion tests at several scales before drawing conclusions about the combustion properties of a treated coal.



Three kg/h laminar flow combustor.

(Photo courtesy of Alberta Research Council)

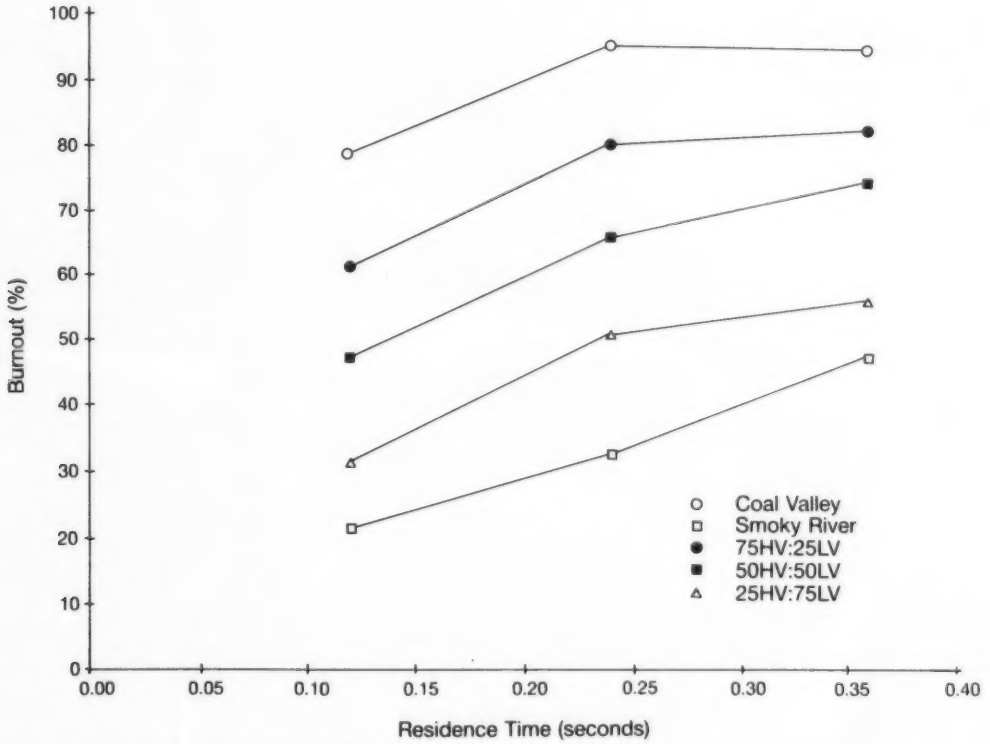
Evaluation of Blending on Combustibility

High-volatile bituminous coals from the foothills region of Alberta are extremely reactive and can be burned in a wide range of boilers, but they are somewhat low in calorific value for coals that must be transported long distances to markets. Conversely, low-volatile bituminous coals used for metallurgical purposes have a high calorific value but a low combustion reactivity. Therefore, it has been reasoned that the reactivity of the low-volatile bituminous coals and the calorific value of the high-volatile coals might be increased by blending the two. This might allow Alberta coal producers to offer new products able to satisfy customer specifications in a way that could not be met by either parent coal alone.

To determine the effects of blending on combustion characteristics, flame stability and carbon burnout tests were performed on 25:75, 50:50 and 75:25 blends of low-volatile and high-volatile bituminous coals, as well as on the individual parent coals. Testing was done using thermogravimetric analysis, entrained flow combustion and laminar flow combustion.

When the parent coals were tested, it was found that the high-volatile coal burned more rapidly than the low-volatile coal. Also, the high-volatile coal had lower ignition and burnout temperatures than the low-volatile coal, as measured by the thermogravimetric analyser.

Results from the entrained flow combustor tests of the blended coals showed that carbon burnout was equal to the sum of the results from the two parent coals. In the laminar flow combustor, with a self-sustained flame, the high-volatile coal ignited and burned in the first half of the combustor, while the low-volatile coal was mostly consumed in the second half. Wall temperature profiles and carbon burnouts of the blends were intermediate to those of the parent coals. However, the 50:50 blend showed a positive interaction of the coals, having the high initial combustion of the high-volatile coal and the combustion characteristics of the low-volatile coal in the latter stages of combustion. These two factors contributed to a higher-than-expected carbon burnout. The results suggest that blends of a certain composition may produce a suitable boiler fuel. Larger-scale combustion tests would be needed to confirm the flame stability and carbon burnout properties.



(Source: *Effect of Blending on the Combustion Properties of Dissimilar Alberta Coals*, Chambers A.K., R. Zacharkiw, D.E. Ungarian and M. Malychuk, Alberta Research Council, March 1988)

Prediction of Coal Combustibility

In a project carried out by Esso Resources Canada Limited of Calgary, it was postulated that the identification and development of commercially valuable coal deposits would be assisted by an ability to determine combustion characteristics from core hole samples rather than from expensive burn tests that require large quantities of coal. Furthermore, the methods currently used to estimate the combustion behaviour of coals can be misleading. Therefore, the primary objective of a project initiated in 1985 and concluded in 1987 was to demonstrate that combustion characteristics can be predicted more accurately, quickly and less expensively using an alternative to the current geological method of classifying coals.

While boiler systems are designed to handle coals possessing various and variable amounts of combustible material (as indicated by volatile matter measurements), it is known that coals containing similar amounts of volatile matter can behave very differently in combustion tests.

This is thought to be caused by different assemblages of macerals. Thus, volatile matter can be thought of as a measure of the sum of the properties of all the component macerals. However, coals having similar amounts of volatile matter can have very different amounts of individual macerals. This is thought to be the explanation for variable combustion performance.

Consequently, the research approach used in this study involved measuring the concentration of the vitrinite maceral and determining whether or not the amount of vitrinite present in a coal sample influenced combustion performance.

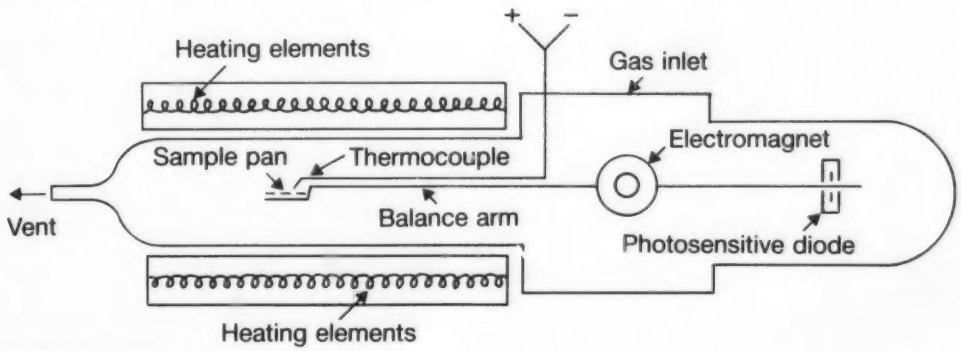
During the first year of the study, 13 vitrinite concentrates derived from coal were tested for thermal reactivity by pyrolysis at 1 300°C and

The results of ignition tests and reflectance microscopy investigations have demonstrated that correlations exist between the geochemistry of coal and combustion characteristics.

combustion at 900°C. The vitrinite concentrations of each sample were determined by measuring reflectance with a microscope. Good correlations were established between thermal reactivity and reflectance characteristics, allowing the researchers to make predictions about the combustion behaviour of four test coals. Subsequent testing revealed that these predictions were accurate approximately 75 per cent of the time. This supported the initial hypothesis that coal rank and maceral composition influence combustion behaviour, at least on the laboratory scale.

During the second year, the predictive procedure was applied to a wider range of coals, including bituminous and subbituminous coals. The predicted char values for combustion at 900°C were derived from coal feed reflectograms and compared to actual char values resulting from combustion testing. Good agreement was found between predicted and measured results. The technique was found to be superior to the use of volatile matter measurements when predicting the combustion behaviour of coals containing more than 25 per cent of the inertinite maceral. Thus, the technique is especially promising for lower-rank western Canadian coals.

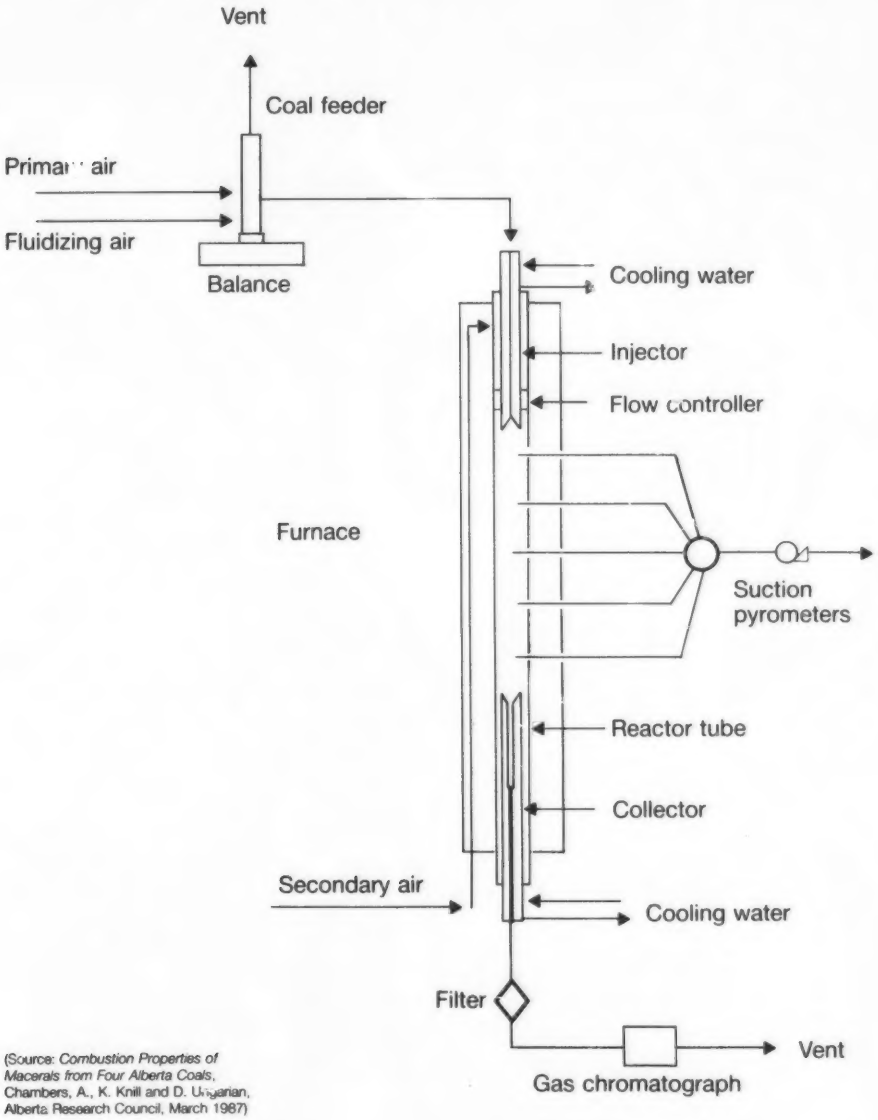
Schematic of the Thermogravimetric Analyzer



(Source: *Combustion Properties of Macerals from Four Alberta Coals*, Chambers, A., K. Knill and D. Ungarian, Alberta Research Council, March 1987)

A planned attempt to relate reflectance measurements to full-scale test burn information was abandoned because insufficient public domain test burn data were available. It was concluded, however, that vitrinite optical reflectance represents a potentially useful technique, which, with further development, might be suitable for in situ mapping of coal combustibility through down hole or surface geophysical methods.

Schematic of the Entrained Flow Combustor



(Source: *Combustion Properties of Macerals from Four Alberta Coals*, Chambers, A., K. Knill and D. Ungarian, Alberta Research Council, March 1987)

Causes of Spontaneous Combustion of Western Canadian Coals

While the ability of coal to burn readily in the presence of oxygen and an ignition source is the primary reason it is a highly desirable fuel, an undesirable characteristic of coal is its tendency to ignite spontaneously while stored in stockpiles or in transit from mine to market.

Although researchers for years have been attempting to explain the process of spontaneous combustion, little is known about the mechanism. It is generally believed, however, that moisture must be present and oxygen is adsorbed onto fresh coal surfaces, but no one knows how spontaneous combustion is initiated or sustained.

From 1986 to 1988, an investigation at the University of Calgary focused on three possible mediators of the spontaneous combustion reaction: trace metals, free radicals and the exinite maceral.

This study concentrated on one western Canadian, high-volatile bituminous coal known to be susceptible to spontaneous combustion. Proximate, ultimate and petrographic analyses were made of this coal and it was also analysed for trace metals. The as-received coal, along with a portion which had been washed to remove most of the minerals, and other samples to which manganese or cobalt were added, were subjected to moist air treatment. Then they were analysed by electron spin resonance spectroscopy (ESR) for changes in the amount of peroxides and free radicals on fresh coal surfaces. Another sample, enriched to 15 per cent exinite, was given the same treatment and analysis.

It was found that changes in the trace metal content did not cause any significant temperature changes within the coal, although the ESR results did show that trace metals altered the peroxide/free radical concentrations. This was especially true for cobalt. Maceral enrichment apparently caused no detectable difference in ESR analysis results or in thermal response.

It was concluded that no substantial evidence could be found for the hypothesis that any of these three substances plays a major role in spontaneous combustion.

Spontaneous Combustion Technical Committee

On November 13, 1987, the Alberta Office of Coal Research and Technology sponsored a one-day symposium on the spontaneous combustion of coal. It was held at the University of Calgary in conjunction with a coal research workshop attended by 150 participants. Three of the six speakers at the Spontaneous Combustion Symposium were from Australia, France and the United States. They described current research in their respective countries, while the other speakers described recent developments in Canada.

Based on findings presented at the symposium, it was decided that more research should be carried out in Alberta. Consequently, a Spontaneous Combustion Technical Committee was formed comprising representatives from Gulf Canada Resources Ltd., Obed Mountain Coal Company Limited, Coal Mining Research Company, Saskatchewan Energy and Mines, and the Alberta Office of Coal Research and Technology. Its primary function is to fund research projects that will likely produce mutual benefits for all the technical committee members.

Spontaneous Combustion of Thermally Treated Coals

In 1988, some members of the Spontaneous Combustion Technical Committee sponsored a review of literature on the chemistry of spontaneous combustion, with particular emphasis on thermally treated coals. This is especially relevant to low-rank western Canadian coals because they must be thermally dried to reduce their delivered cost per unit of energy in distant markets such as Ontario and Pacific Rim countries. However, thermal drying makes these coals more susceptible to spontaneous combustion.

The study, performed by the Coal Mining Research Company in concert with Bio-Chem Consulting Ltd., the Alberta Research Council and the Canada Centre for Mineral and Energy Technology, found that the properties of a coal change after thermal treatment in a vacuum or air or in an inert atmosphere, and this is caused by changes in the surface chemistry and the porous structure of coal. It is believed that thermal drying causes polar

groups such as carboxyl (–COOH) or phenol (–OH) to form at the coal surface. These groups cause an increase in the moisture retention capacity of coal, expressed as an increase in the equilibrium moisture content. Because the absorption of moisture is thought to be a key step toward spontaneous combustion, it follows that any thermal drying process which causes the formation of polar groups probably will lead to an increase in the equilibrium moisture content and an increased likelihood that spontaneous combustion will occur. As moisture is absorbed, heat (called the heat of wetting) is generated. This enhances the reaction of oxygen with the polar groups to form peroxygen groups. The latter are highly reactive and decompose readily to form free radicals. As the peroxygen groups decompose, more heat is generated. If the heat cannot be dissipated, spontaneous combustion can occur.

This characteristic is further aggravated in the case of low-rank coals because their pore surface area tends to increase when they are dried. Therefore, it was concluded that, with respect to spontaneous combustion, low-rank coals should not be dried to less than their equilibrium moisture content.

In reviewing current methods of testing the spontaneous combustion susceptibility of coals, it was concluded that internationally accepted standard test methods do not exist. It was further concluded that:

- warm or hot coal should be cooled before being stockpiled or placed in a silo;
- drying process conditions can be altered to affect the susceptibility of coal to spontaneous combustion; and
- treating a coal to reduce the heat of wetting is as important as treating it to inhibit oxidation.

Further Developments

Most of the coal combustion studies reported here have helped the Alberta Research Council develop small-scale test facilities that are ideally suited for studies involving coal samples weighing 100 kg or less. At the same time, ARC researchers have also developed numerical modelling skills which have become valuable in interpreting the results of these small-scale combustion tests. This expertise in coal combustion has led to a significant research program at ARC aimed at determining the gasification properties of Alberta coals.

Also, the Alberta Office of Coal Research and Technology has been participating in some fundamental investigations by the International Energy Agency of pulverized coal combustion. The principal findings of these studies will be reported in another technology transfer booklet.

Coal Macerals

Coals are composed of discrete organic materials called macerals. There are three major types: vitrinite, exinite and inertinite. They arise from the wide variety of vegetable matter which decomposed eons ago and was then converted into coal. Vitrinite, for example, is derived from wood and bark, whereas exinite is said to arise from a wide variety of plant materials such as resins, waxes and algae. Inertinite, however, is formed from charred material, perhaps resulting from forest fires.

Each of these macerals can be identified when viewed in reflected light through a microscope, and each has characteristic properties. For example, vitrinite tends to have a higher oxygen content than other macerals. This results in a high volatile matter content. Exinite has a higher hydrogen content and has the highest volatile matter content. By contrast, inertinite has a higher carbon and a lower hydrogen content, giving it a lower volatile matter content.

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Contacts

For additional information about coal combustion studies at the Alberta Research Council, contact:

Dr. Arvid Hardin
Director
Coal and Hydrocarbon Research Department
Alberta Research Council
P.O. Bag 1310
Devon, Alberta
T0C 1E0

Telephone: (403) 987-8118

Further details about the method developed by Esso Resources Canada to predict coal combustibility are available from:

D.E. Weckman
Oil Sands and Coal Department
Esso Resources Canada Limited
237 4th Avenue S.W.
Calgary, Alberta
T2P 0H6

Telephone: (403) 237-3737

For more information about the spontaneous combustion of Alberta coals, contact:

Dr. F.W. Bachelor
Department of Chemistry
University of Calgary
2500 University Drive N.W.
Calgary, Alberta
T2N 1N4

Telephone: (403) 220-5341

and

R.G. Chopiuk
President
Coal Mining Research Company
P.O. Bag 1400
Devon, Alberta
T0C 1E0

Telephone: (403) 987-8195

Additional copies of this publication are available from:

Information Centre
Alberta Energy/Forestry,
Lands and Wildlife
Main Floor, Bramalea Bldg.
9920 - 108 Street
Edmonton, Alberta
T5K 2M4

Telephone: (403) 427-3590

Information Centre
Alberta Energy/Forestry,
Lands and Wildlife
Main Floor, Britannia Bldg.
703 - 6th Avenue, S.W.
Calgary, Alberta
T2P 0T9

Telephone: (403) 297-6324

For more information about A/CERRF, contact:

Senior Manager,
Technology Development
Scientific and Engineering Services and
Research Division
Alberta Energy
2nd Floor, Pacific Plaza
10909 Jasper Avenue
Edmonton, Alberta
T5J 3M8

Telephone: (403) 427-8042

Telex: 037-3676

Fax: (403) 422-0975

More can be learned about the Alberta Office of Coal Research and Technology by contacting:

Chairman
Alberta Office of Coal Research and Technology
Alberta Energy
2nd Floor, Pacific Plaza
10909 Jasper Avenue
Edmonton, Alberta
T5J 3M8

Telephone: (403) 427-8042

Telex: 037-3676

Fax: (403) 422-0975

Other publications in this series which are available and deal with coal research include:

An Economic Analysis of Coal Pipeline Systems, 6 pages, January 1987.

Opportunities to Use Coal in Enhanced Oil Recovery, 8 pages, April 1988.

Development of an Agglomeration Process to Beneficiate and Transport Alberta Coals, 14 pages, June 1988.

Gasification of Western Canadian Coals, 14 pages, June 1988.

Coal Research Centre, Devon, 10 pages, August 1988.

Co-processing Studies of Alberta Subbituminous Coals, 14 pages, December 1988.

Mathematical Modelling of Automedium Cyclones, 10 pages, January 1989.

The Technical Committee Approach to Coal Research, 6 pages, January 1989.

Advanced Coal Mining Techniques for Alberta, 10 pages, March 1989.